SIMULATION OF BULK MATERIALS SEPARATION PROCESS IN SPIRAL SEPARATOR

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МОДЕЛЮВАННЯ ПРОЦЕСУ СЕПАРАЦІЇ СИПКИХ МАТЕРІАЛІВ НА СПІРАЛЬНОМУ СЕПАРАТОРІ

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ABSTRACT

The design of spiral separator in question is based on the analysis of bulk materials separators. It has advantages over the known devices. Spiral separator is maintenance-friendly compact mechanism with a simple drive. As a tool, the spiral separating screen is used. This allows intensifying the separation process and separate bulk materials into several fractions.

The empirical and theoretical dependence for describing the process of bulk materials separation by spiral separator is obtained. The methodology of definition coefficients of mathematical equations is developed. They depend on the material fractional composition and its initial settings. The experimental research for defining the separation coefficients is conducted. The processed pellets and flax fibre shives are used. The mathematical model of bulk materials separation by spiral separator is obtained and the method of determining bulk materials separation coefficients by designing a type of spiral separator is developed. The concept of spiral separator efficiency coefficient characterizing the separation degree of the bulk material fine fraction is introduced. The dependence to justify the length of the spiral separator cage is obtained.

РЕЗЮМЕ

На основі аналізу конструкцій сепараторів сипких матеріалів запропонована конструкція спірального сепаратора, що має низку переваг над відомими конструкціями. Зокрема, спіральний сепаратор є компактним, має простий привод та зручний в обслуговуванні. Крім того, використання у якості робочого органу спіралеподібного решета дозволяє інтенсифікувати процес сепарації та здійснювати розділення сипкого матеріалу чи суміші матеріалів на кілька фракцій.

Одержані емпірико-теоретичні залежності для опису процесу сепарації сипкого матеріалу на спіральному сепараторі. Розроблено методику для визначення коефіцієнтів сепарації, які входять в отримані рівняння і залежать від фракційного складу матеріалу та початкових параметрів шару матеріалу. За розробленою методикою здійснено експериментальні дослідження, що дозволили на прикладі паливних гранул та костриці льону-довгунця визначити значення коефіцієнтів сепарації для цих матеріалів. Проведений комплекс теоретичних та експериментальних досліджень дозволив описати перебіг процесу сепарації сипких матеріалів (паливних гранул, костриці льону-довгунця) на спіральному сепараторі. Отримана математична модель процесу сепарації сипких матеріалів на спіральному сепараторі та розроблена методика визначення коефіцієнтів сепарації придатні для опису процесу сепарації і інших сипких матеріалів на спіральному сепараторі запропонованої конструкції. Введено поняття коефіцієнта ефективності роботи спірального сепаратора, що характеризує ступінь відокремлення дрібної фракції з сипкого матеріалу. Отримано залежність для обґрунтування довжини спіралеподібного решета сепаратора.

INTRODUCTION

To separate materials into fractions by size, shape, weight and aerodynamic properties in agriculture, manufacturing and food processing, various separators are used. The most common are separators with flat and drum cage. The vibratory separators and air separators with helical surfaces are used as well *(Ciobanu V. et al., 2015; Dadak V., 2015; Falko O., 2014; Ivancu B. et al., 2015; Kartashevich, S., 2001; Paraschiv G. and Manole C., 2015)*. Most of the separators combine several separation types. The famous design have a number of drawbacks: big sizes and high metal content (characteristic of separators with flat and drum cages); complex driving system of working bodies (characteristic of vibratory separators); low degree of chamber filling and productivity (characteristic of air separators, separators with drum cages, spiral bodies and surfaces).

Scientific research is aimed at finding new technological and technical solutions to intensify the process of bulk materials separation *(Falko O., 2014; Kartashevich, S., 2001)*. The key to a successful solution to this problem is the development of mathematical models describing the separation process of bulk materials that would justify the rational design-technological parameters of separators. Development of mathematical models is based on the analysis of the separation process and determining the factors that most influence its course.

During the theoretical description of the separation process the following factors must be considered:

- separation type;
- separator design peculiarities;
- uneven distribution of particles of different material size or its components;
- a wide range of particle sizes and particle mass of bulk material or mixture of materials;
- different physical-mechanical properties of the material;
- variation of separation intensity depending on the material parameters (material layer width, the feeding rate, etc.) and movement along the working bodies or surfaces;
- fraction content in the initial material layer or its mixture.

In most cases, the separation process is described using empirical and theoretical or empirical dependences with ratios determined experimentally. Typically, these dependencies are not universal and are suitable to describe the separation process of bulk material or mixture of materials. Thus, to describe the separation process of bulk materials carried out with the modern separators it is necessary to conduct additional theoretical and experimental investigations.

MATERIALS AND METHODS

Two types of bulk materials were used in the research: processed pellets and flax fibre shive. According to EN 14961-2 the content of fine fraction in the pallets packaging unit should not increase 1.0 %. During production process of pallets this parameter exceeds the norm. Taking this into account, it is necessary to separate the fine fractions from pellets before packaging.

Quality of pellets and briquettes made from flax shive depend on the raw material properties. One of the major characteristics of the raw material is its fraction. The best mechanical properties of the pellets and briquettes are achieved if the fraction is less than 10 mm. If it is not in line with this requirement – the shive should be pre-processed, i.e. necessary fractions should be separated.

The method of determining separation factors for bulk materials (pellets, shive) in a spiral separator study included the investigation of bulk material fractional composition with the help of particle-size analysis *(Khaylis G. and Fedorus Y., 2004)*. Fractional composition was determined as the ratio of individual fractions mass to the total weight of bulk material:

$$N_j = \frac{M_j}{M_m} \cdot 100\%, \tag{1}$$

where N_j – quantity of bulk material particle of *j* fraction, [%];

M_j – *j* fraction mass of bulk material, [kg];

M_m – total weight of bulk material, [kg].

As a result, the content of fine fractions, below 10 mm, is 29.5%. Fine fraction content, below 10 mm, which should be separated, is 39.8%.

After the fraction content was defined, a portion of the bulk material was weighed and loaded into the spiral separator (figure 1) *(Dudarev I., 2016)*. The spiral cage was adjusted to the fraction to be separated with sizes 0.9x10 mm.

The spiral separator is equipped with two spiral cages, with similar separation processes. During separation, the bulk material was moved with the disc. Fine fractions went through the cage holes into the container. Separation intensity was defined with the coefficient μ :

$$\mu_i = \frac{m_i}{M_{0i} \cdot l_i}, \tag{2}$$

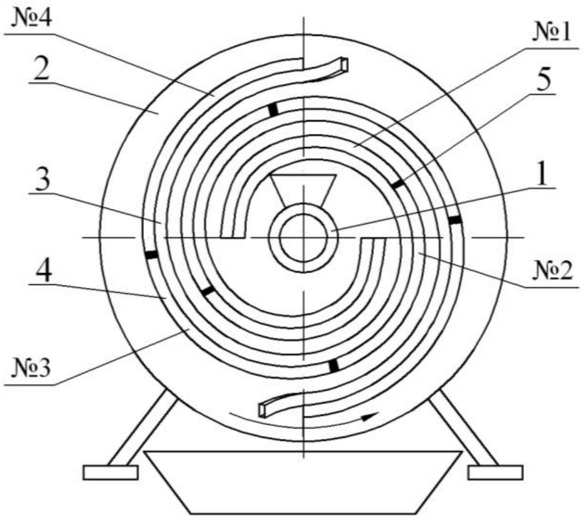
where μ_i – the separation coefficient on section i of the spiral cage, [m^{-1}];

M_{0i} – mass of fine fraction in the bulk material before separation on section i of the spiral cage, [kg];

m_i – fine fraction mass separated on section i of the spiral cage with the length l_i, [kg];

l_i – length of section i of the spiral cage, [m].

Theoretical investigations included the major statements of bulk materials separation theory and own investigation outcome *(Dudarev I., 2016; Khaylis G. and Konovaliuk D., 1991)*.



a

b

Fig. 1 – Scheme (a) and picture (b) of spiral separator laboratory machine

1 – bin; 2 – disc; 3 – spiral cage; 4 – spiral container; 5 – dividing plates; №1, №2, №3, №4 – sectors

RESULTS

The spiral separator (figure 2) contains a frame, driving unit, bin, disc with two similar spiral cages and spiral containers for fine fractions as well as buffers for big and fine fractions.

The operation of the spiral separator is shown on the example on one of the spiral cage, since the second cage is operated similarly. The bulk material is fed to the bin and moved through the spiral cage. The fine fraction material goes through the cage holes into the spiral container. Big fraction material is moved to the end of the spiral cage and then to the big fraction material buffer, fine fraction material goes to the fine fraction material buffer.

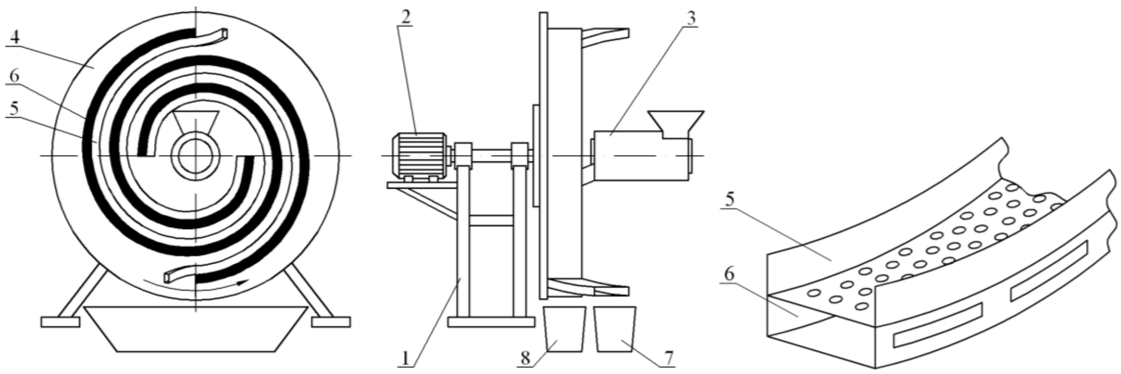


Fig. 2 – Spiral separator

1 – frame; 2 – drive; 3 – buffer; 4 – disc; 5 – spiral cage; 6 – spiral container;
7 – big fraction container; 8 – fine fraction container

The separation process is complex in terms of description, because the location of particles of different materials or sizes is random. Besides, the particles to be separated are reduced in the process, making the process description even more complicated and requiring introduction of assumptions.

Since the separation coefficient changes according the cage length, in order to provide a more detailed description, the spiral cage should be divided into similar sections $l_1 = l_2 = ... = l_i = l$. Every section is assumed to have a constant separation value $\mu = \text{const}$.

Let's investigate a portion of bulk material, fed to the separator, containing fine fraction M_0 to be separated. During short time span dt the bulk material layer will pass the surface of the spiral cage with the length dl. The probability of fine fraction separation is μdl. At the beginning, the fine fraction to be separated was M_0, and after it passed the spiral cage section with the length $l + dl$ (where l – is the length of the spiral cage section passed by the material layer, [m]; dl – increase of the spiral cage section, [m]), fine fraction mass became $M_0 - dM$. Thus, dM is the separation value (mass of the bulk material separated fine fraction). Then, dM / M_0 will be the relevant separation value. The equation of relevant separation value dM / M_0 and separation probability describes separation process in the spiral separator as follows:

$$-\frac{dM}{M_0} = \mu dl . \quad (3)$$

The experimental value of the separation value μ is defined at a certain width of material layer, because it influences significantly the separation coefficient. The bigger the width, the worse the separation process is. That is why, in order to achieve required separator productivity, the cage width should be increased. In this case, better separation conditions are possible for the same material volume fed to the separator at similar intervals.

Using the separation equation (3), let's define the mass of the fine fraction material M_i, which remains unseparated in the i-section of the spiral cage with length l_i:

$$M_i = M_{i-1} e^{-\mu_i l_i}, \ i = \overline{1, n}; \quad (4)$$

where n – number of sections with the length l of the spiral cage and spiral container.

Mass of the separated fine fraction material m_i during bulk material separation of each spiral cage section:

$$m_i = M_{i-1} - M_i . \quad (5)$$

Total mass m_Σ of the bulk material separated fine fraction on the spiral cage:

$$m_\Sigma = \sum_{i=1}^{n} m_i = M_0 - M_n . \quad (6)$$

The previous investigations determined the appropriateness of the cage spiralling according to the logarithmic spiral with equation $\rho(\varepsilon) = \rho_0 e^{m^* \varepsilon}$, here $m^* = (\rho - \rho_0) / l$ (where l – spiral cage length between the radii ρ_0 and ρ, [m]; ρ_0 – the smallest radius of the spiral cage, [m]; ε – angle of spiral, [rad.]).

Let us define the separation process changing the spiral cage radius. The length of a section can be defined as $l_i = \frac{1}{m^*}(\rho_i - \rho_{i-1})$ (where ρ_{i-1} and ρ_i – radii at the beginning and the end of the i-section of spiral cage).

Considering the presented dependences, the equation (4) will be:

$$M_i = M_{i-1} \cdot e^{-\frac{\mu_i(\rho_i - \rho_{i-1})}{m^*}} . \quad (7)$$

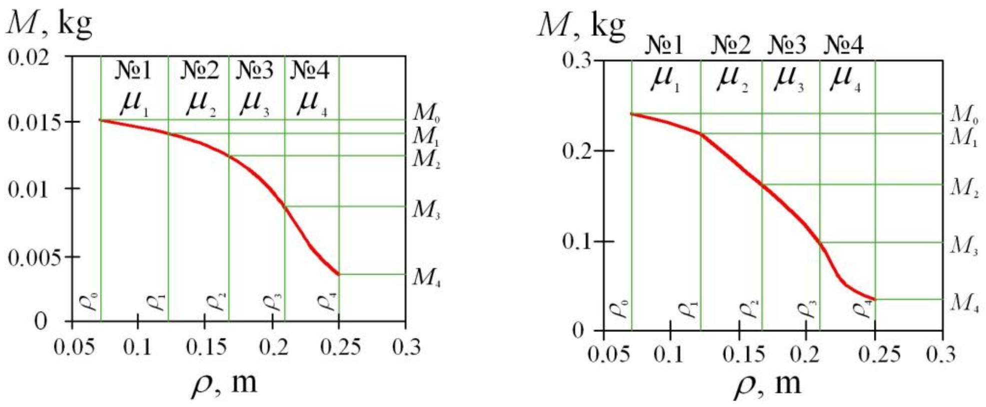
The radii values of the spiral cage for the equation (7) are defined with the equation $\rho(\varepsilon) = \rho_0 e^{m^* \varepsilon}$. The angle of the cage spiral is defined as follows:

$$l_i = \int_{\varepsilon_{i-1}}^{\varepsilon_i} \sqrt{\rho^2(\varepsilon) + \rho'^2(\varepsilon)} d\varepsilon = \frac{\rho_0 \sqrt{1 + m^{*2}}}{m^*} \left(e^{m^* \varepsilon_i} - e^{m^* \varepsilon_{i-1}} \right), \quad (8)$$

from where we obtain:

$$\varepsilon_i = \frac{1}{m^*}\ln\left[\frac{m^* l_i}{\rho_0\sqrt{1+m^{*2}}} + e^{m^*\varepsilon_{i-1}}\right]. \tag{9}$$

Applying the obtained dependences (7) – (9), and separation values μ_i, the fine fraction mass M variation diagrams depending on the radius ρ of the spiral cage in each section of the length l are built (figure 3).



a *b*

Fig. 3 – Fine fraction mass M variation diagrams in the separation process depending on the radius ρ of the spiral cage in sections with $\rho_0 = 0.07\ m$ and $m^* = 0.18$

a – separation of the pellets with $\mu_1 = 0.263\ m^{-1}$; $\mu_2 = 0.507\ m^{-1}$; $\mu_3 = 1.323\ m^{-1}$; $\mu_4 = 4\ m^{-1}$;

b – separation of the flax fibre shive with $\mu_1 = 0.4\ m^{-1}$; $\mu_2 = 1.11\ m^{-1}$; $\mu_3 = 1.97\ m^{-1}$; $\mu_4 = 4\ m^{-1}$

In order to show the length of the spiral cage L_s where the fine fraction will be separated from the bulk material, we take the logarithm of equation (4):

$$\ln(M) = \ln\left(M_0 e^{-\mu_m L_s}\right), \tag{10}$$

Where: M – mass of the fine fraction material remaining in the bulk material after separation on the spiral cage with the length L_s, [kg];

M_0 – mass of fine fraction in the bulk material before separation, [kg];

μ_m – average value of bulk material separation coefficient per spiral cage length L_s, [m^{-1}];

L_s – spiral cage length, [m].

Having transformed the equation (10), we obtain:

$$L_s = -\frac{1}{\mu_m}\cdot\ln\left(\frac{M}{M_0}\right), \tag{11}$$

Mass of fine fraction in the bulk material before separation is determined according to dependence (1):

$$M_0 = \frac{M_m N}{100}, \tag{12}$$

where N – number of fine fraction particles in the bulk material before separation, [%];

M_m – total mass of bulk material before separation, [kg].

The average value of the bulk material separation coefficient per spiral cage length is defined as follows:

$$\mu_m = \sum_{i=1}^{n}\frac{\mu_i}{n}. \tag{13}$$

Let's introduce the efficiency coefficient of spiral separator, to characterize separation degree of fine fractions from the bulk material. The coefficient value is defined as follows:

$$K_s = \frac{M}{M_0}. \tag{14}$$

The lower the coefficient value K_s, the more efficient the separator operates. If, for example, the efficiency coefficient is $K_s = 0.03$, it means that 3% of fine fraction material remained unseparated, and 97% was separated. Substituting the average separation coefficient μ_m and spiral separator efficiency coefficient K_s in the equation (11), we obtain:

$$L_s = -\frac{\ln(K_s)}{\sum_{i=1}^{n}\frac{\mu_i}{n}}. \quad (15)$$

Based on the equation (15) the diagrams are built (figure 4), which show impact of coefficients μ_m and K_s on the spiral cage length L_s, where the necessary degree of the fine fraction separation should be obtained. At reduction of the spiral separator efficiency coefficient K_s and separation coefficient μ_m the spiral cage length L_s increases.

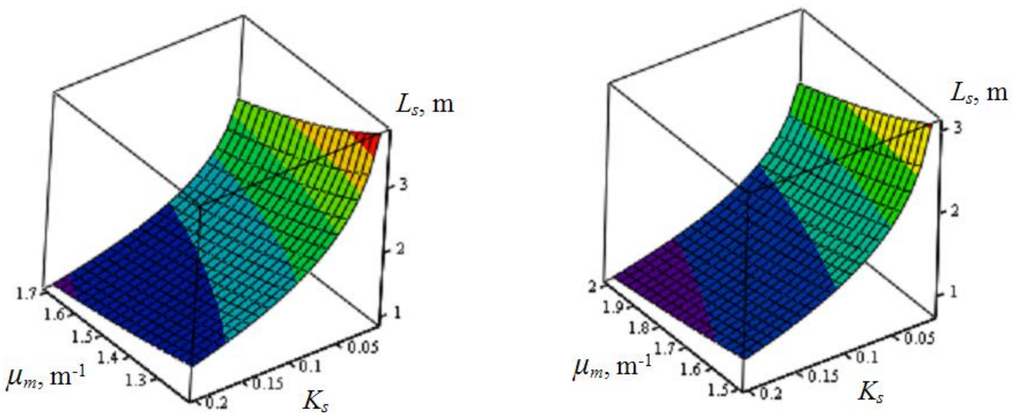


Fig. 4 – Diagrams showing the impact of the coeffficents μ_m and K_s on the lengths L_s of the spiral cage

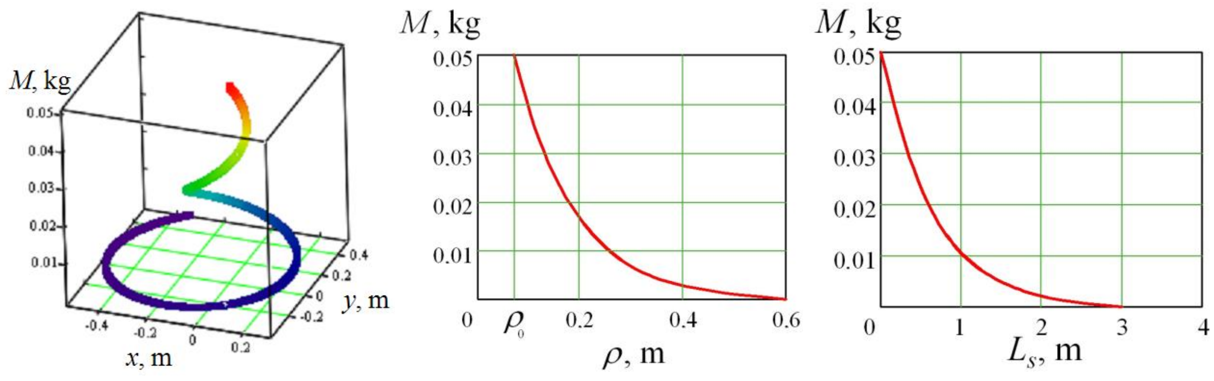
a – for pellets; b – for flax fibre shive

The calculations made according to the equation (15) allowed us to demonstrate the length of the separator spiral cage: 1) for pellets with $\mu_m = 1.523$ m^{-1} and $K_s = 0.03$ the length of the cage should be $L_s = 2.3$ m; 2) for flax fibre shive with $\mu_m = 1.87$ m^{-1} and $K_s = 0.05$ the length of the cage should be $L_s = 1.6$ m. The defined spiral cage will ensure the required separation degree of fine fractions in the bulk material. The conducted investigations allowed obtaining the mathematical model of bulk material separation in the spiral separator which will be represented in coordinates xyM:

$$\left.\begin{array}{l} x = \rho_0 e^{m^*\varepsilon}\sin\varepsilon; \\ y = \rho_0 e^{m^*\varepsilon}\cos\varepsilon; \\ M = M_0 e^{-\mu_m \frac{\rho_0\sqrt{1+m^{*2}}}{m^*}\left(e^{m^*\varepsilon} - e^{m^*\varepsilon_0}\right)}, \end{array}\right\} \quad (16)$$

where $\varepsilon \in [\varepsilon_0; \varepsilon_{\max}]$, $\varepsilon_{\max} = \frac{1}{m^*}\ln\left[\frac{m^* L_s}{\rho_0\sqrt{1+m^{*2}}} + e^{m^*\varepsilon_0}\right]$.

The first and the second equation of the system (16) show the spiral of the cage. By means of the mathematical model (16) and equations (4), (7) the diagrams are built (figure 5 and figure 6) showing the separation model.

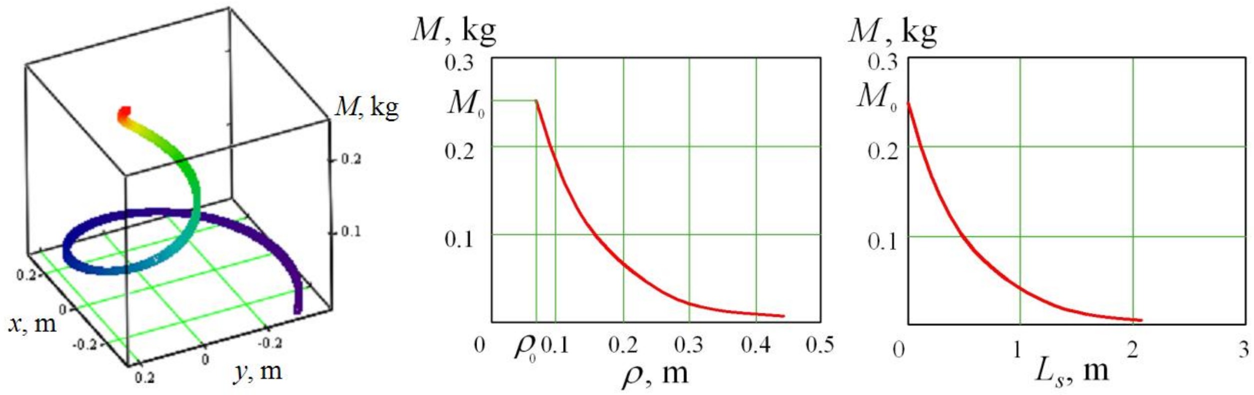


a *b* *c*

Fig. 5 – The curves showing separation of the pellets in the spiral separator with

$K_s = 0.01$**;** $\mu_m = 1.523$ m^{-1}; $M_0 = 0.05$ kg; $\varepsilon_0 = 0$ rad.; $\rho_0 = 0.07$ m and $m^* = 0.18$

a – fine fraction mass M variation diagram in the material along the spiral cage; b – fine fraction mass M variation in the material with changed radius ρ of the spiral cage; c – fine fraction mass M variation in the material with changed length L_s of the spiral cage



a *b* *c*

Fig. 6 – The curves showing separation of the flax fiber shive in the spiral separator with

$K_s = 0.02$; $\mu_m = 1.87$ m^{-1}; $M_0 = 0.25$ kg; $\varepsilon_0 = 0$ rad.; $\rho_0 = 0.07$ m and $m^* = 0.18$

a – fine fraction mass M variation diagram in the material along the spiral cage; b – fine fraction mass M variation in the material with changed radius ρ of the spiral cage; b – fine fraction mass M variation in the material with changed radius ρ of the spiral cage;

c – fine fraction mass M variation in the material with changed length L_s of the spiral cage

CONCLUSIONS

The design of spiral separator in question allows reducing sizes of the separator due to the installation of the spiral unit and reducing metal and power consumption. Besides, the spiral separator is ergonomic and ensures high level separation.

The conducted investigations allowed describing the bulk material separation process (pellets and flax fibre shive) with the spiral separator. The mathematical model of the bulk material separation with the spiral separator is obtained; the method for coefficient definition is developed, which can also be applied for other materials.

The definition of spiral separator efficiency coefficient is introduced, characterizing the degree of separation of the fine fractions. The dependence representing the spiral cage length is obtained.

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